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A DISSERTATION SUBMITTED TO THE FACULTY
OF THE DIVISION OF THE PHYSICAL SCIENCES
IN CANDIDACY FOR THE DEGREE OF DOCTOR OF
PHILOSOPHY

DEPARTMENT OF PHYSICS

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Sparking Potentials at Low Pressures

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At gas pressures less than the Paschen critical value the sparking potential rises rapidly with decrease in pressure. Measurements are difficult because of undesired discharges over longer paths than the intended one. A sparking tube has been constructed with which measurements have been made on air, carbon dioxide, hydrogen, and helium up to 24 kv with nickel electrodes, and on air with a stainless steel cathode. The results are compared with those of Carr, of Cerwin, and of Penning. The equations of the straight portions of the sparking potential curves are of the form $V = a + b \log pd$. From these equations the number of electrons released by the cathode per positive ion impact has been calculated by a method described by Dempster.

THE variation of the sparking potential of a gas with electrode separation and gas pressure was first extensively investigated by Paschen,¹ who announced the law that, with a uniform electric field, the sparking potential is a function of the product of distance d and pressure p . As the product diminishes the sparking potential decreases until, at a critical value, it becomes a minimum for a given gas. For still smaller values of the product, the sparking potential increases rapidly. For these smaller values measurements are difficult since any longer path permits a discharge at a lower voltage. Carr² made an investigation of the sparking potentials of a number of gases over a rather wide range of values of the product pd , but his highest voltage was only 1800. In his apparatus two flat electrodes were separated by an ebonite ring which covered the electrode edges and thus permitted the discharge only in a region of uniform field. Penning³ found an anomalous behavior for helium: there were as many as three different values of the sparking potential for the same gas pressure. At a pressure of 0.84 mm between electrodes separated 2.6 cm, sparks occurred at 500, 1500, and 5000 volts.

In this laboratory Cerwin⁴ has recently measured the sparking potentials of air between flat nickel electrodes separated 2–10 mm, using voltages which he believed to be as high as 80 kv. The results were in agreement with Paschen's

law. The present problem began as an effort to obtain similar data for other gases, with the gas flowing continuously through the sparking chamber to minimize the concentration of possible impurities from the glass walls or the electrodes.

APPARATUS

Figure 1 is a diagram of the apparatus. It was found very early that when the pressure was less than the critical value corresponding to the minimum sparking potential, a discharge would probably take place between the high potential electrode and the pump, reservoir, or gauge, and occasionally initiate the main spark. To prevent this, a pair of electrodes a was inserted in each of the connections to the sparking tube, the two electrodes being separated by a smaller distance than the main sparking distance, the one nearest the tube having no external connection and the other being grounded. Because of leakage over the glass it is not believed that the device was completely effective in preventing arc currents.

The first sparking tubes were patterned after those used by Cerwin.⁴ It was practically impossible to make such tubes so that the discharge was confined to the space between the flat electrode surfaces when the pressure was less than the critical value; discharges could be seen terminating on the back surfaces of the electrodes. A second design of sparking tube used electrodes having flat faces but conical backs ground into glass seats and held snugly in place by springs. The angle of the cone was made large enough so that when the electrodes were

¹ E. T. Paschen, *Ann. d. Physik* **37**, 69 (1889).² W. R. Carr, *Phil. Trans. Roy. Soc. A* **201**, 403 (1903).³ F. M. Penning, *Proc. Roy. Acad. Amsterdam* **34**, 1305 (1931).⁴ S. S. Cerwin, *Phys. Rev.* **46**, 1054 (1934).

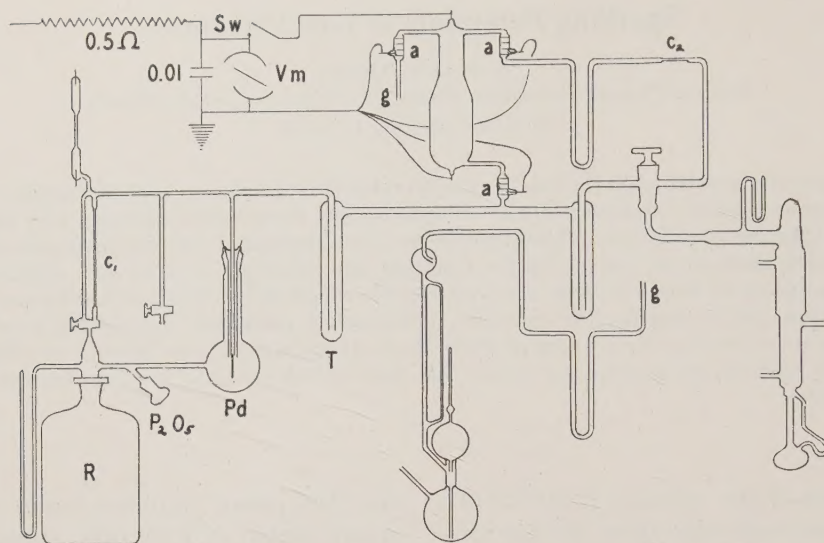


FIG. 1. Diagram of apparatus.

outgassed by induction heating the expansion did not crack the glass. Although there was no visible discharge to the backs of these electrodes, a discharge terminated at their edges. To prevent this, flat disk electrodes were enclosed, except for the central portion, in fired steatite. The glass

supporting structure became sputtered, and the steatite enclosure broke.

Figure 2 shows the construction of a tube which provides one discharge path longer than any other, over which the electric field is not seriously distorted, and which is sufficiently removed from any dielectric that might become sputtered. The cathode is a spun cylindrical shell with a hemispherical end. The anode is a solid nickel cylinder with hemispherical ends. These latter were turned to fit fairly closely to a template and then polished with emery paper. The glass rings sealed in at the end of the cathode shell prevent a discharge from the edge of the shell to the anode up to the highest voltage used, which was about 24 kv. The first tube constructed had a stainless steel cathode, which rusted. When the tube was opened the pitted spots on the two electrodes resulting from the sparks were found distributed over a small area on each electrode centered approximately on its axis.

The design of the tube was suggested by the nature of the electrostatic fields surrounding two opposing point charges. The equipotential surfaces are nonintersecting shells about each of the charges. If spherical conducting shells replace two surfaces, with a sufficient potential difference, and with a gas enclosed between them, a spark should take place along the line of greatest separation, where the field is approximately uniform. If R and r are the radii of the outer and

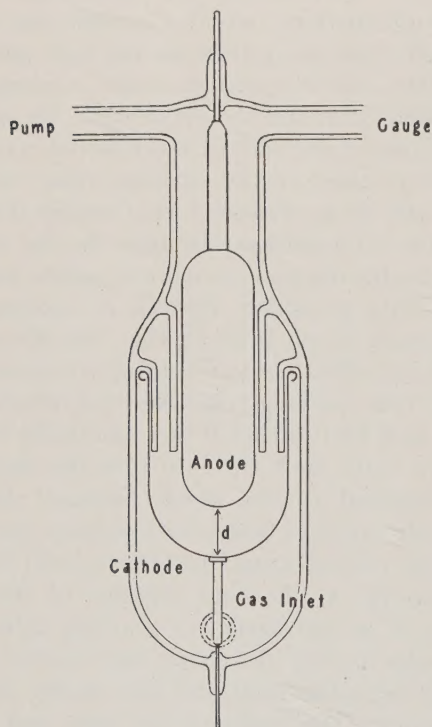


FIG. 2. Diagram of sparking tube.

inner spheres, respectively, and if d is the sparking distance, then it is obvious that $d > (R-r)$. Furthermore, if the spheres are non-intersecting, $d < 2(R-r)$. Hence, the range of values of d permitted for given spheres is small; and the field is most satisfactorily uniform for spheres of not too different radii.

PREPARATION OF GASES

For air the reservoir R (Fig. 1) was filled to a pressure of about 10 cm, and left with the air in contact with the P_2O_5 for several hours. The trap T prevented mercury vapor from the reservoir manometer and stopcock grease vapor from entering the sparking tube. Temperatures were kept constant to within $\pm 1^\circ C$. In taking the data the voltage was raised a small amount, the

electrostatic voltmeter was read, and the voltage was applied to the sparking tube. Application of the voltage lasted about fifteen seconds. If no spark resulted, indicated by a "drop-back" of the voltmeter pointer, the voltage was raised and applied again. The voltage was not sufficiently constant to take advantage of any possible delay in the formation of the spark longer than about fifteen seconds, and no significant delay of even that length was observed. As soon as a spark occurred, the gas pressure was observed with the McLeod gauge.

Carbon dioxide was chosen after consideration of the work of Buchmann⁵ and of Klemperer.⁶ Buchmann showed that air lies between CO_2 and H_2 in the number of secondary electrons produced per centimeter path at 1 mm pressure, over an extended velocity range of the primary electrons. Klemperer estimated the yield of electrons by the cathode per positive ion impact at the minimum sparking potential to be 0.66 percent for air, 0.09 percent for CO_2 , and 0.74 percent for H_2 . The carbon dioxide was obtained by evaporation of dry ice which had been pulverized and packed into a flask. Any air and a considerable volume of CO_2 were pumped off before the gas was admitted to the previously evacuated reservoir.

Tank helium was admitted to the reservoir through an auxiliary liquid air-cooled charcoal trap. Charcoal was also placed in the trap T . This trap, then, operating at low pressures, was very effective in removing any remaining impurity. Tests with a pocket spectroscope indicated a high degree of purity.

A palladium valve served both to purify and to regulate the flow of hydrogen.

RESULTS

The results are shown graphically in Fig. 3. Since Paschen's law is fairly well established only one sparking distance, namely 17.2 mm, was used for the nickel cathode tube. Sparking potentials near the minima are computed from Carr's data and plotted as the broken curves. The transitions to the curves A , B , C , and D are not very good. However, Carr used brass electrodes and rubber

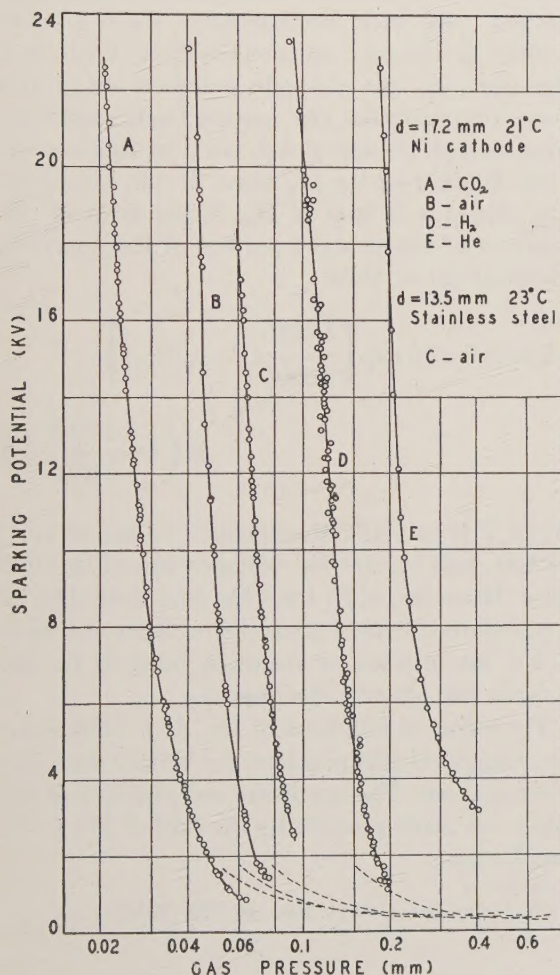


FIG. 3. Sparking potential as a function of gas pressure.

⁵ E. Buchmann, Ann. d. Physik 87, 523 (1928).

⁶ O. Klemperer, Zeits. f. Physik 52, 650 (1928). See I. Langmuir and K. T. Compton, Rev. Mod. Phys. 2, 181 (1930).

insulation, with the consequence that the electrode system could not be outgassed.

It is apparent that the two curves *B* and *C* for air do not satisfy the relation that for a given sparking potential pd is a constant. The cathode was of stainless steel in one case and of nickel in the other. Anderson⁷ has found for a 1-mm gap in high vacuum a breakdown voltage of 120 kv for stainless steel and of 96 kv for nickel. If a proportionate difference were supposed to hold for discharges in air at much lower voltages, pd for the stainless steel cathode at, say, 18 kv might be compared with that for the nickel cathode at 14.4 kv. These values agree approximately with those observed in the present experiments for $pd=0.80$. The observation at high pressures that the sparking potential is independent of electrode material probably does not hold for low pressures. The small temperature difference accounts for a very small part (0.005) of the discrepancy, since the cooler gas exerts less pressure for the same density. In general the sparking potential is of the same order of magnitude as the value obtained by Cerwin. At 20 kv pd (nickel cathode) = 0.75, whereas Cerwin obtained about 0.82.

There is no indication of any anomaly in the behavior of helium at the pressures and sparking distance used.

The equations of the straight portions of the curves are, in terms of V_0 in kv, d in mm, and p_0 in mm at 0°C: For

- (1) Air—stainless steel cathode, $d=13.5$ mm—
 $V_0=1.72-128.45 \log p_0 d$ $pd < 0.95$
 nickel cathode, $d=17.2$ mm—
 $V_0=-2.5-121.5 \log p_0 d$ $9 < V < 14$
 $V_0=-27.9-309.0 \log p_0 d$ $14.5 < V < 21$

TABLE I. Cathode emission in sparks at low pressure.

V (VOLTS)	AIR-STAINLESS STEEL-NICKEL			CO ₂ -Ni		H ₂ -Ni	
	$s(V)$	$m(V)$	$m(V)$	$s(V)$	$m(V)$	$s(V)$	$m(V)$
3000	2.70	3.99	4.34	4.10	4.88	0.43	10.39
4000	2.45	4.56	4.97	3.75	5.63	0.386	12.03
6000	2.00	5.98	6.54	3.04	7.74		
10000	1.35	10.13	11.17	2.05	14.13		
14000	0.92	16.94	18.80	1.4	25.27		
18000	0.65	27.24	30.43				

⁷ H. W. Anderson, Elec. Eng. **54**, 1315 (1935).

- (2) Carbon dioxide—nickel cathode, $d=17.2$ mm—
 $V_0=-18.3-80.3 \log p_0 d$ $9 < V < 16$
 $V_0=-38.9-129.1 \log p_0 d$ $16 < V < 23$
 (3) Helium—nickel cathode, $d=17.2$ mm—
 $V_0=107.8-179.4 \log p_0 d$ $11 < V < 23$
 (4) Hydrogen—nickel cathode, $d=17.2$ mm—
 $V_0=46.2-115.1 \log p_0 d$ $8 < V < 15.5$
 $V_0=37.4-82.1 \log p_0 d$ $15.5 < V < 22$

SECONDARY ELECTRONS FROM POSITIVE ION IMPACT

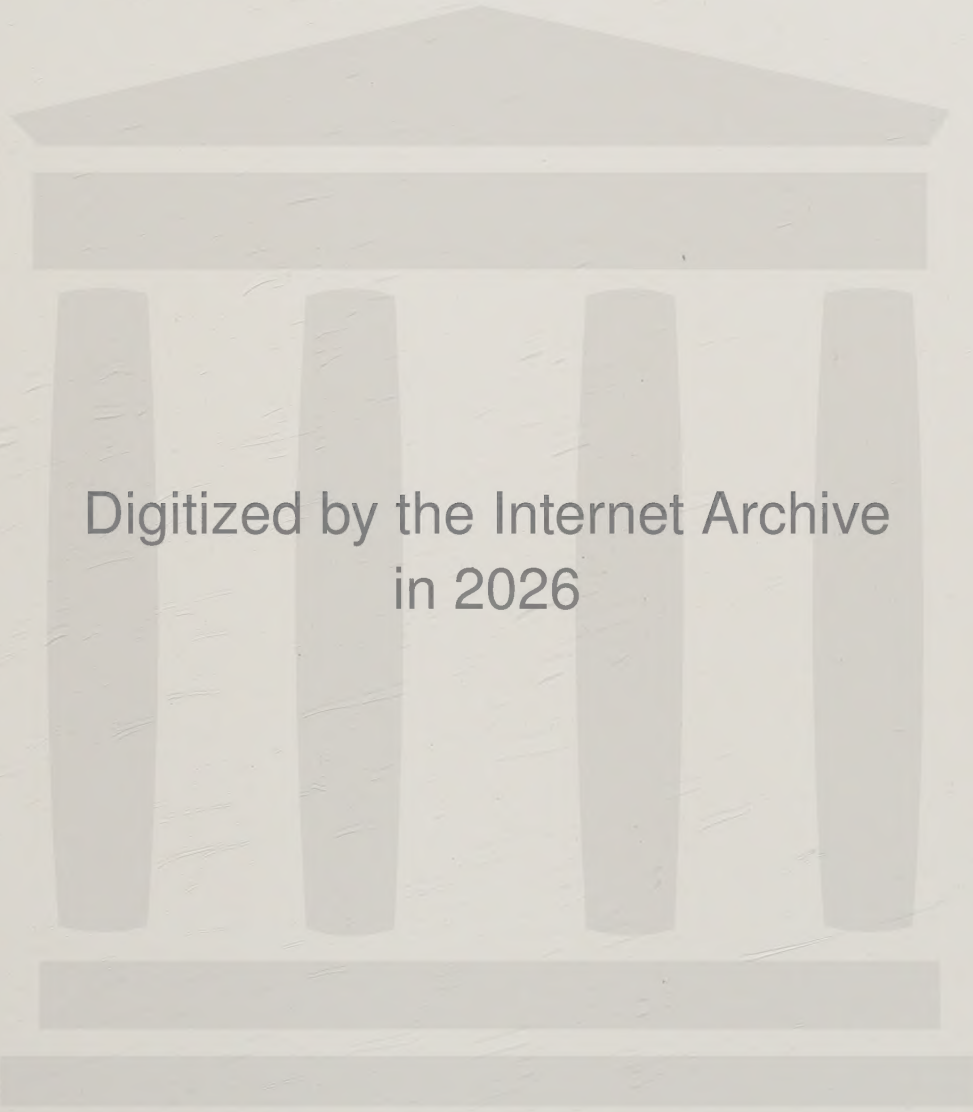
Dempster⁸ has shown that the cathode emission of electrons under positive ion bombardment may be a primary factor in the mechanism of the spark discharge at low pressures, and that the number of such electrons may be calculated from equations for sparking potential curves with known values of the ionizing efficiency of the primary electrons in the gas. From Dempster's method and with Buchmann's⁵ data for the number of ionizing collisions $s(V)$ in 1 cm at 1 mm pressure, the cathode emission $m(V)$ has been computed for the gas-electrode combinations, except helium-nickel, used in this experiment. If $V=a+b \log pd$, where V is in kv, d is in mm, and p is in mm of Hg, is the form of the equation of the straight portion of the sparking potential curve, then

$$s(V)m(V)=10 \exp \left[\frac{2.3026}{1000b} (V-1000a) \right] \times \left(1 - \frac{2.3026}{1000b} V \right)$$

where V is in volts. Buchmann's values of $s(V)$ for CO₂ and H₂ are for voltages less than 5000 volts. However, $s(V)$ for CO₂ may probably be extrapolated. Table I gives the resulting values of $m(V)$, the number of electrons released by the cathode per positive ion impact.

The writer is indebted to Dr. A. J. Dempster, who suggested this problem, for helpful direction and criticisms. The successful construction of the tubes was made possible by the skill of Mr. C. C. Van Hespen.

⁸ A. J. Dempster, Phys. Rev. **46**, 728 (1934).



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